Alcator C-Mod

Divertor and Edge Physics program

Relationship to other programs
General program description
Transport
Neutrals
Impurities
High heat flux & particle handling

Presented by B. Lipschultz
Contributions from B. LaBombard & J. Terry,
T. Chung , O. Grulke, S. Lisgo

C-Mod in relation to other tokamaks

- C-Mod operation overlaps that of other tokamaks in edge/divertor dimensionless parameters w/different dimensional parameters
- Some of the differences in edge & divertor dimensional parameters are
  - Higher density (similar to ITER in divertor)
  - Higher divertor opacity to Lyα with diffusive neutrals (similar to ITER)
  - Higher parallel heat flux (300-500 MW/m^2, 3-5xother tokamaks, similar to ITER)
  - Higher SOL plasma pressures (similar than ITER)
- The range in dimensionless parameters can be different too
  - High collisionality ($\sim$ 1-4 x ν* for other tokamaks and ITER)
  - Short $\lambda_{0,mfp}/\lambda_{SOL}$ & $\lambda_{0,mfp}/\lambda_{Div}$ ($\sim$ 2-4x less than other tokamaks, similar to ITER)
- Different scalings for neutral penetration may help unfold the roles of atomic and plasma physics
- Operation with Mo first wall makes an important contribution
  - ASDEX-U is gradually converting to W

C-Mod in relation to other tokamaks

- The C-Mod boundary research program complements work being done around the world

Research area	C-Mod	Other tokamaks

Plasma transport
   Turbulence imaging $\longrightarrow$
   Turbulence statistics $\longrightarrow$
   Radial flux analysis $\longrightarrow$
	Turbulence visualization $\longrightarrow$
	 Probes, D_α $\longrightarrow$
	 from particle balance $\longrightarrow$
		NSTX, DIII-D (core)
		 DIII-D, JET
		 DIII-D, JET (by C-Mod)

Impurities (through 'lifecycle')	Mo sources, transport, screening, redeposition Mo physical sputtering	C sources, transport, screening, redeposition C chemical erosion
Neutral transport	main chamber recycling Compare w/div leakage Hydrogen and metals, B n-n collisions important	Emphasis on divertor effects, cryopump, T codeposition w/C Kinetic neutrals
ELM effect on SOL and divertor	Concentrating on small or no ELM regimes	Major program on DIII-D, JET

Relation to IPPA goals

The C-Mod boundary physics program addresses a number of issues listed in the IPPA document.

- 3.1.1 Turbulence and transport (3.1.1.1, 3.1.1.2, 3.1.1.3)
  - Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems
- 3.1.4 Plasma boundary physics (3.1.4.1, 3.1.4.2, 3.1.4.3)
  - Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes.
- 3.3.1 Profile control (3.3.1.4, 3.3.1.5 - low n_e divertor operation)
  - Assess profile control methods for efficient current sustainment and confinement enhancement in the advanced tokamak, consistent with efficient divertor operation, for pulse lengths much greater than energy confinement times.
- 3.4.1 Plasma technologies (3.4.1.3 - Plasma facing components)
  - Develop enabling technologies to support the goals of the scientific program, including methods for plasma measurements, ….; develop plasma facing components….

C-Mod Boundary physics program

- Optimize the performance of fusion devices through
  - minimal core impurities (radiation, fuel dilution),
  - maximal first-wall lifetime, power handling
  - divertor design for optimal impurity/neutral compression and pumping

- To those ends we concentrate our research on
  - Edge plasma transport
    - Our primary emphasis because it is the determining factor for heat and particle loadings, impurity sources and transport
  - Neutral dynamics and fueling
  - Impurities

  - Develop predictive capability scaleable to reactor (ITER)

- We also identify and develop hardware and techniques for
  - Heat flux handling & density control

Edge Transport

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Status

- Time-averaged profiles
  - Used to extract $\Gamma_\perp$ transport fluxes
  - Imply non-diffusive transport
- Turbulence studies
  - visualization techniques developed
  - turbulence dynamics & statistics characterized
- Numerical simulations
  - Matched some expt'l measurements
  - Time-averaged profiles specified, not predicted
  - Turbulence drive is ballooning-like
- Exploring connection to density limits
- SOL flows
  - strong, unexplained, but appear to be affecting the core

Goals/Program

- Explore transport scalings and role of plasma vs neutral physics
- Fully identify/characterize turbulence & role in transport
- Employ 1st principle simulations to reproduce
  - Turbulence characteristics
  - Time-averaged profiles
- Predict power/particle flux footprint on ITER divertors and wall
- Develop capability to modify radial transport
- Understand role of edge flows in transport (core and SOL)

Time-averaged SOL profiles and plasma flows

Goals

Determine relationships between time-averaged profiles and …

- ◆ radial particle and heat fluxes
- ◆ poloidal variations in transport
- ◆ plasma flows
- ◆ scalings with plasma physics parameters
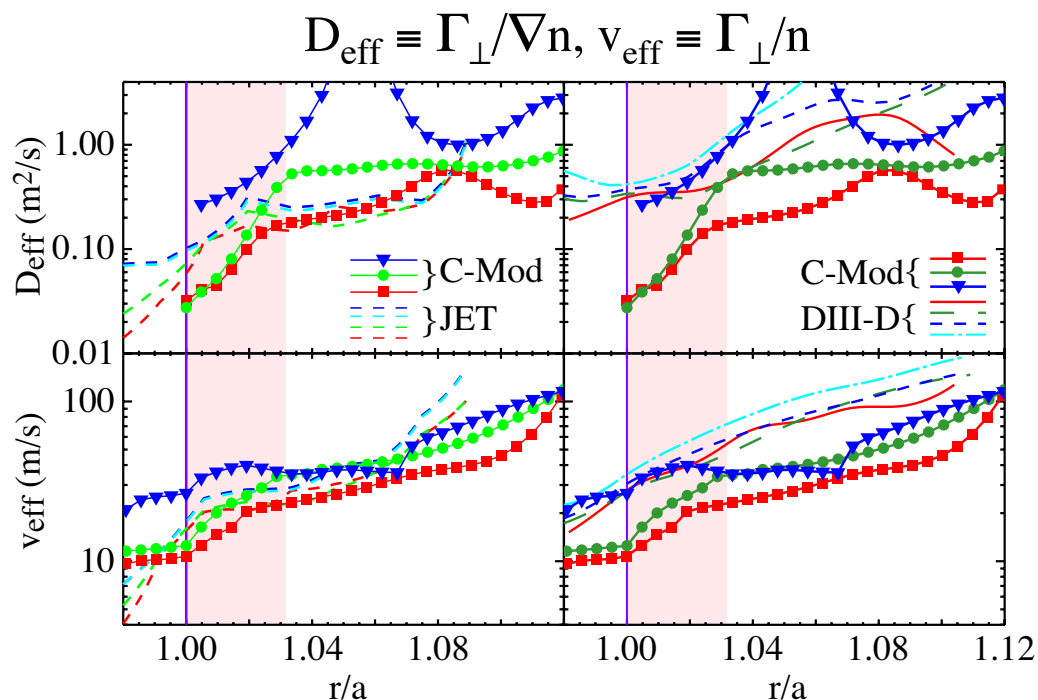- ◆ role of atomic vs plasma physics

…important for predicting main-chamber wall interaction, divertor performance and impurity control in ITER
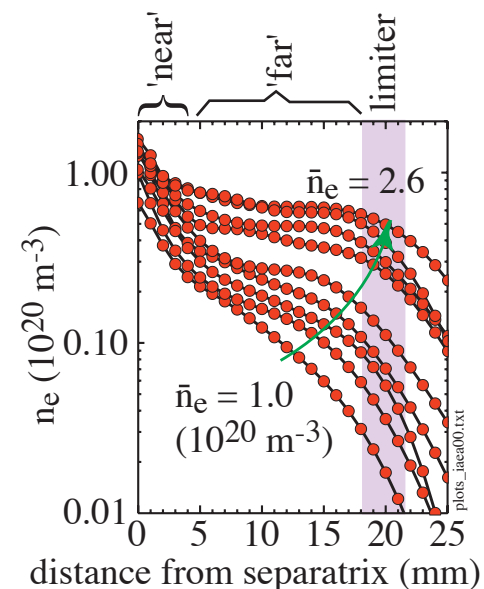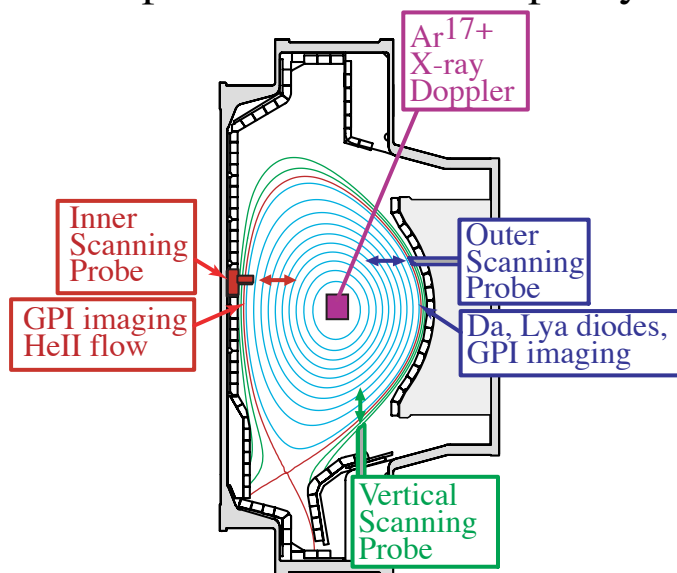
Methods

- ● Detailed SOL diagnostic set:
  - ◆ Langmuir-Mach probes at inner/outer SOL
  - ◆ Inner/outer array of tangential fiber views
  - ◆ Radially-resolved imaging of recycling light
    - ■ extract radial transport fluxes

Remarkably similar far SOL transport on very different experiments

$$D_{eff} \equiv \Gamma_\perp/\nabla n, \quad v_{eff} \equiv \Gamma_\perp/n$$

Goal - empirical approach to characterize/understand transport
- provide scalings to BPX
- help determine underlying physics

Method - $\Gamma_\perp$ from particle balance analysis

Results (new from JET collab.)
- Transport in JET far SOL
  - Convective
  - Little dependence on ν^*, ρ^*, β
  - Roughly invariant with machine size ($a^{0.25}$)
- Neutral penetration likely playing a role in SOL profile shapes

Plans
- MP submitted to DIII-D for H-mode plasmas
- Further analysis of JET data and new expts.
- Expand comparisons to other tokamaks
- Evaluate implications for ITER

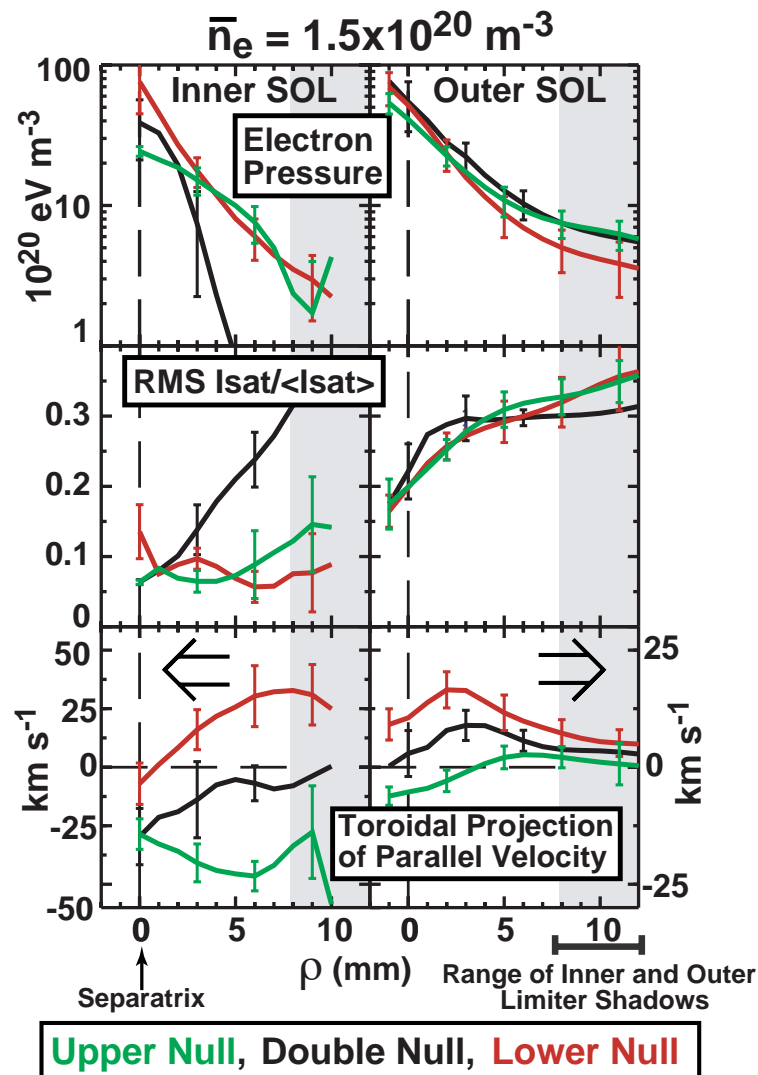# Neutral penetration in ITER similar to C-Mod => broad far SOL?
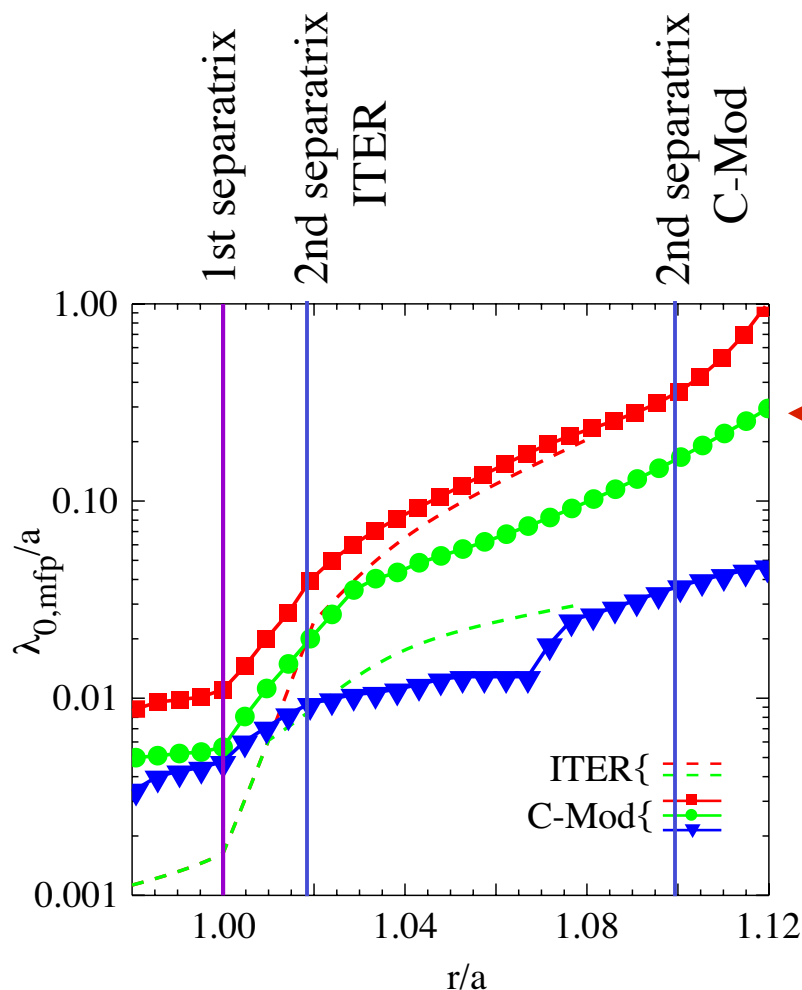
Results

- Scale SOL transport results to ITER
  - Radial flux at second separatrix ~ 10^{23}/s
  - Wall/2nd divertor fluxes important
- Evaluate the transparency of the ITER SOL using SOL profiles from Kukushkin*
  - T_e and n_e are 'high'.
  - SOL opaque to neutrals, consistent with Kukushkin's work, like C-Mod.
  - Non-linear effect on n_e profile shape -> radial 'high recycling' condition?
  - Difficult to predict far SOL profiles

Plans

- Work with ITER modellers
  - Include far SOL v_{eff}
  - Include SOL out to limiters, beyond second separatrix.

* A. Kukushkin et al., NF 43 (2003) 716.

Strong Transport Asymmetries => Strong Plasma Flows

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$\bar{n}_e = 1.5 \times 10^{20}$ m^{-3}

Inner SOL — Outer SOL

Electron Pressure

RMS Isat/<Isat>

Toroidal Projection of Parallel Velocity

ρ (mm)

Range of Inner and Outer Limiter Shadows

Separatrix

Upper Null, Double Null, Lower Null

New Results

- Direct measurements of inner/outer n, T_e profiles and flux tube variation of T_e in USN, DN, & LSN
  - quantifies poloidal heat/particle transport asymmetries
- Fluctuations are measured to be low in inner SOL, independent of topology
  - supports ballooning-like turbulence paradigm
- Near-sonic parallel flows at inner SOL with direction dependent on topology (USN, DN, LSN)
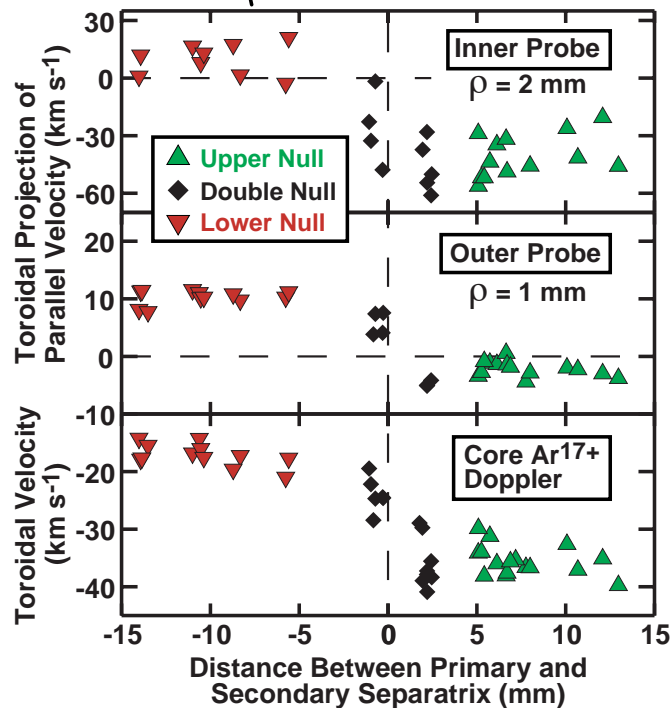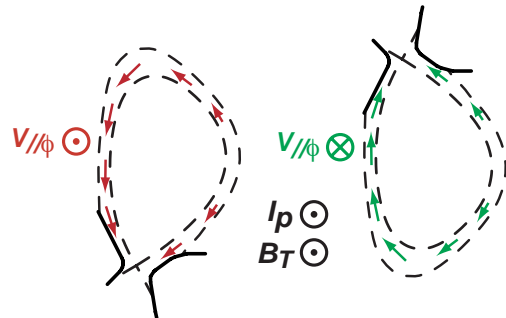 - consistent with flows driven by $\perp$ transport asymmetry

Plans

- Upgrade inner-wall scanning Mach probe
  - Mult. electrodes for flow & fluctuation analysis
- Develop spectroscopic flow measurements
  - He-II, BV CXRS

Transport-Driven SOL Flows and Magnetic Topology
=> Flow Boundary Conditions on Confined Plasma

⊥ transport-driven parallel SOL flows:

$v_{//\phi}$ ⊙ $v_{//\phi}$ ⊗

I_p ⊙
B_T ⊙

Toroidal Projection of Parallel Velocity (km s⁻¹)

Inner Probe
ρ = 2 mm

▲ Upper Null
◆ Double Null
▼ Lower Null

Outer Probe
ρ = 1 mm

Toroidal Velocity (km s⁻¹)

Core Ar¹⁷⁺ Doppler

Distance Between Primary and Secondary Separatrix (mm)

LSN ⟵⟶ USN

New Results

- SOL flows appear to be affecting the core
  - Inner SOL flow momentum appears to couple across the separatrix to core toroidal rotation
  - Topology-dependent L-H power threshold may be caused by SOL flows
  - underlying drive - ballooning-like edge turbulence

Plans

- Explore dependence on parameter ranges (n_e, I_p, B_t), topology (SSEP), neutral effects, L-H power thresholds (MP363, MP375, MP384, MP385,…).
- Better flow measurements at & inside the separatrix
- Address missing physics in 2-D fluid codes
  - B2.5-Eirene (X. Bonnin - IPP Greifswald)
  - UEDGE (A. Pigarov - UCSD, M. Umansky - LLNL)

Quantum leap in camera capability leading to statistical analysis and understanding flows

*Alcator C-Mod*

Goals for turbulence studies

- Connect turbulence to transport…
- Simulations identify turbulence drive
- Simulations predict profiles
- Control turbulence & profiles

Methods

- Probes, "gas-puff-imaging" (GPI) with cameras & diode arrays.

New Results

- New movie camera (shared w/PPPL)
  - Gone from 28 to 300 frame movies
  - Radial & poloidal "blob" propagation
- L- and H- mode turbulence differences
- Poloidal flow direction dependent on magnetic topology
- Drive is ballooning-like (outer edge)
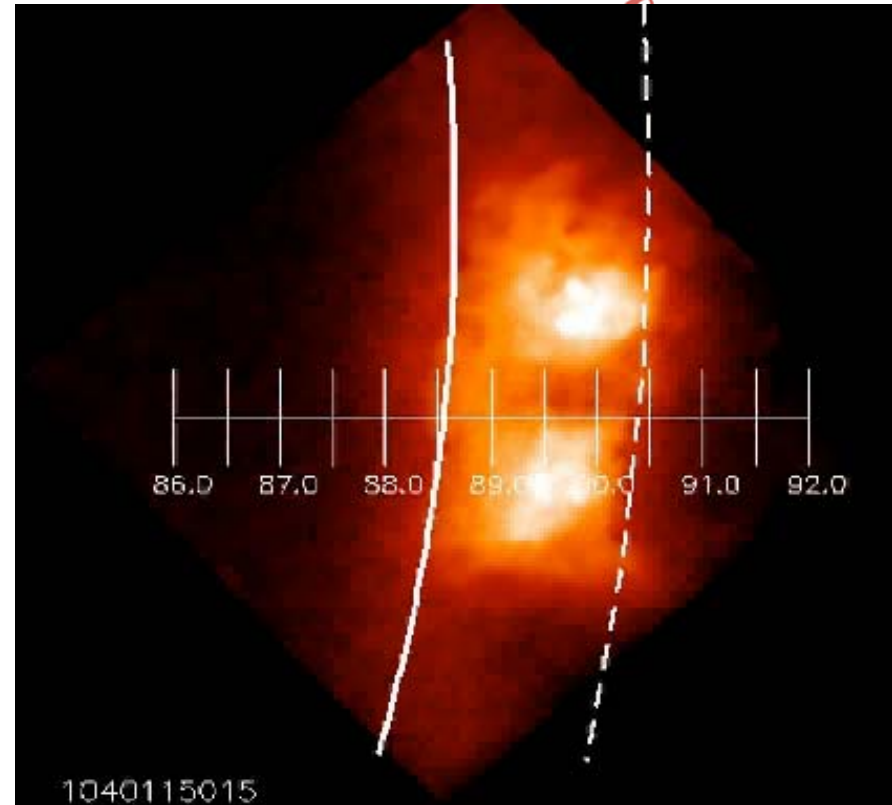
Plans - higher spatial resolution (<1mm),
  - Size & velocity distribution analysis
  - Image an L-to-H transition,
  - Image an ELM event

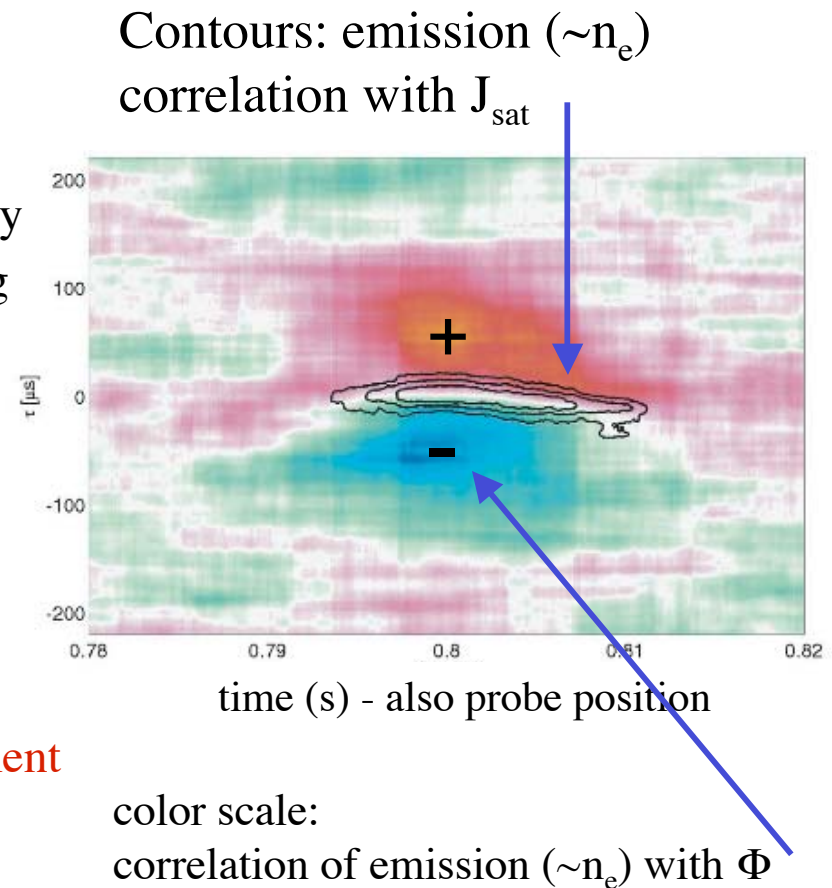# Turbulence correlation along flux tube leads to new data about filament formation & propagation

Method

- Correlate fluctuations along a flux tube between probe ($\tilde{J}_{SAT}$, $\tilde{\Phi}$) & GPI diode array
- Probe insertion across flux tube connecting toroidally to diodes

Results

- Fluctuations correlate along a flux tube
- Probe (J_{SAT}, Φ) correlates with GPI diode array intensity fluctuations.
- n_e & Φ fluctuations: $\pi/2$ phase difference
- Dipole structure consistent with blob/filament creation & propagation.

Plans

- Continued data analysis

Contours: emission ($\sim n_e$) correlation with J_{sat}

time (s) - also probe position

color scale:
correlation of emission ($\sim n_e$) with Φ

"Filament" propagation analysis reveals radial propagation details

Goals

- Study positive ('blob') and negative ('hole') fluctuation propagation

Method

- Conditional averaging & cross-correlation of GPI diode emission measurements

Results

- Self-similar correlation shape
- Radially outward acceleration
- Velocity higher than DIII-D & previous movie measurements

Plans

- Study holes
- Add poloidal array of diode views (good statistics for radial AND poloidal velocity
- Improve spatial resolution (4 -> 2 mm)
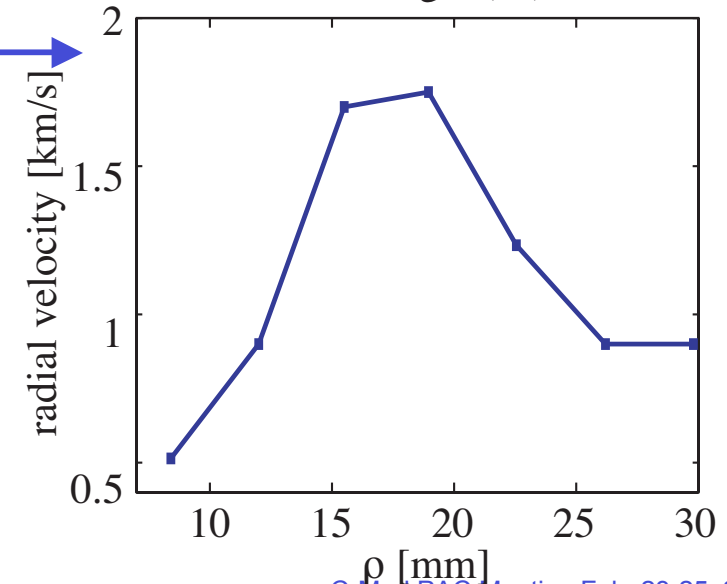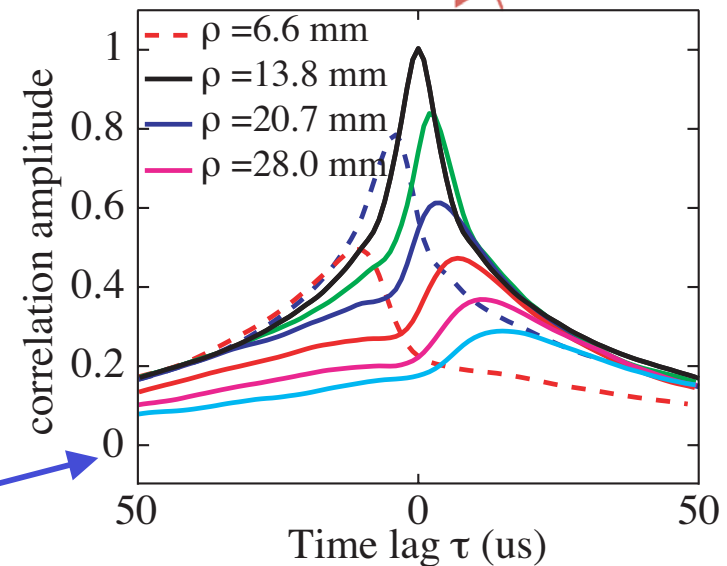
New camera movies confirm probe picture of turbulence role in density limit

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Goal

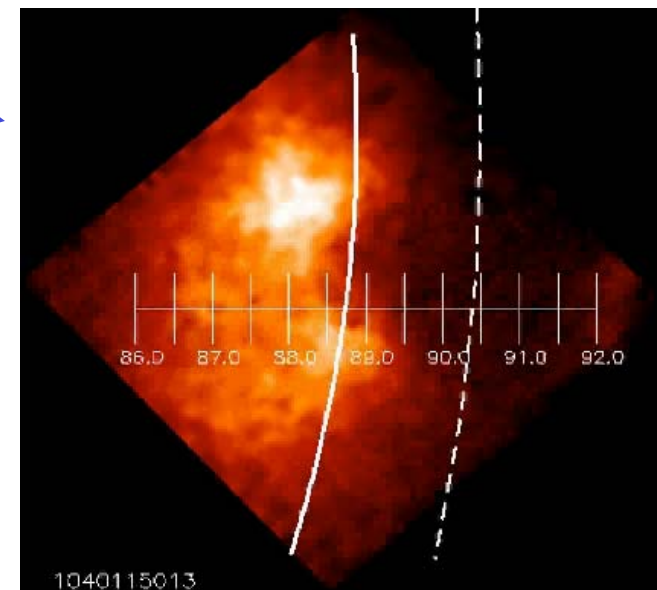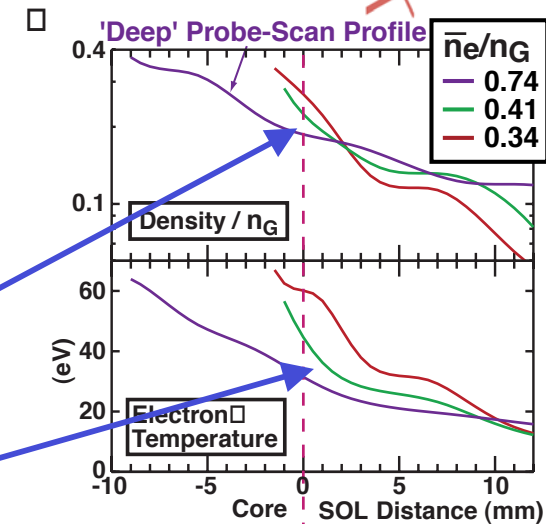Understand the physics of the density limit

New Results

- Camera-measured turbulence mirrors probe results
  - Flat density region moves inside separatrix
  - Near SOL steep gradients disappear
  - Large convective heat losses depress T_e near separatrix
  - Turbulence moves inside separatrix
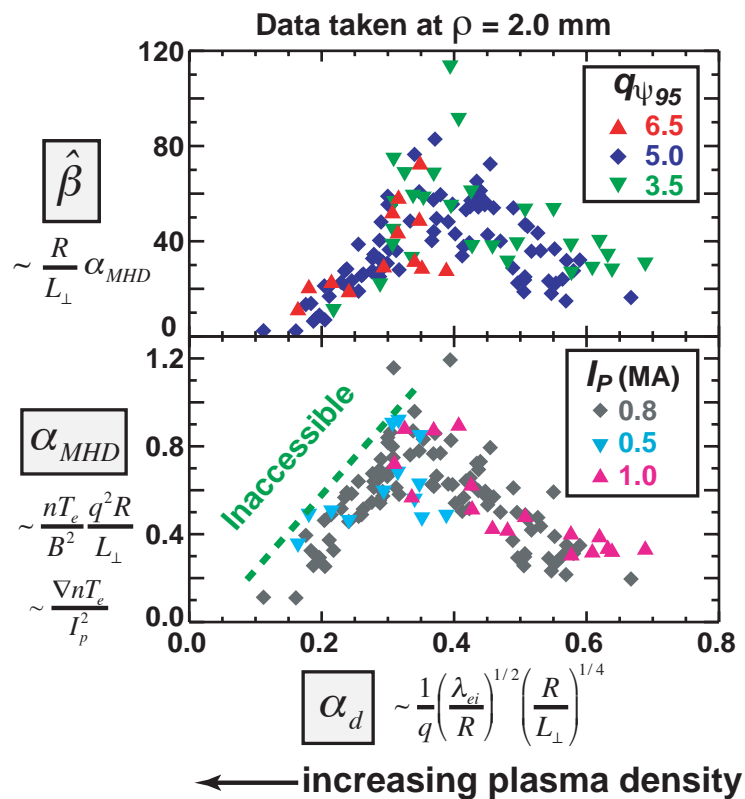 - May lead to core thermal instability

⟹ Suggests shift in balance between perpendicular and parallel transport determines discharge density limit

Plans

- Compare turbulence characterisitics to far Sol and pre-density limit.

'Deep' Probe-Scan Profile

$\overline{n}_e/n_G$
- 0.74
- 0.41
- 0.34

Density / n_G

Electron Temperature

(eV)

Core | SOL Distance (mm)

1040115013

Evidence for Electromagnetic Fluid Drift Turbulence Controlling Edge Plasma State

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Data taken at $\rho = 2.0$ mm

$\hat{\beta}$

$\sim \dfrac{R}{L_\perp} \alpha_{MHD}$

$q_{\psi 95}$
- ▲ 6.5
- ◆ 5.0
- ▼ 3.5

α_{MHD}

$\sim \dfrac{n T_e}{B^2} \dfrac{q^2 R}{L_\perp}$

$\sim \dfrac{\nabla n T_e}{I_p^2}$

Inaccessible

I_P (MA)
- ◆ 0.8
- ▼ 0.5
- ▲ 1.0

$\alpha_d \sim \dfrac{1}{q} \left(\dfrac{\lambda_{ei}}{R} \right)^{1/2} \left(\dfrac{R}{L_\perp} \right)^{1/4}$

← **increasing plasma density**

Background:
- Fully non-linear electromagnetic models of turbulence (Rogers, Drake, Scott, Hallatschek,…) identify 2 controlling parameters:
  - ◆ plasma β (α_{MHD} or $\hat{\beta}$)
  - ◆ collisionality (α_d or $\hat{C}$)

New Results
- Edge pressure gradients scale with I_p^2 and map to a simple function of collisionality, when normalized according to electromagnetic fluid drift turbulence

- Strong endorsement that EMFD turbulence controls plasma transport near separatrix

Plans
- Finish data analysis and publish initial results
- Follow-up experiments:
  - ◆ extend parameter range (B_t -> 8 tesla, I_p -> 1.2 MA)
  - ◆ examine influence of x-point topologies, reversed B
  - ◆ characterize transport fluxes

Edge Fluctuation Statistics: New measures of turbulence dynamics

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Goals

- Statistical properties of SOL turbulence
  - ◆ hope to predict turbulence dynamics & resultant transport in macroscopic sense
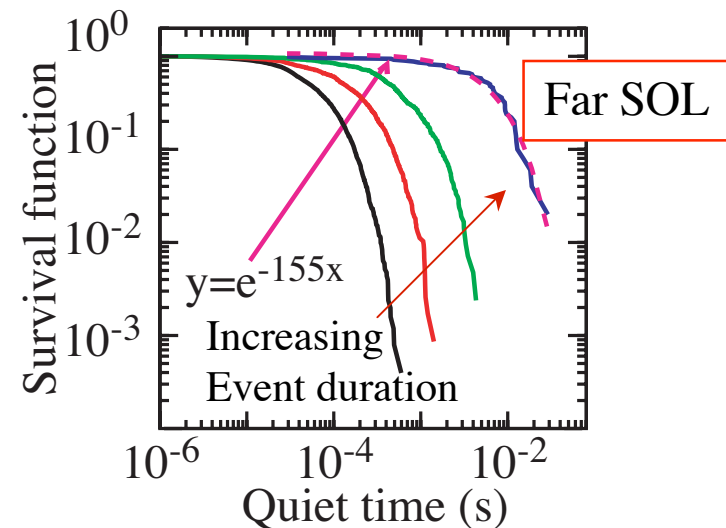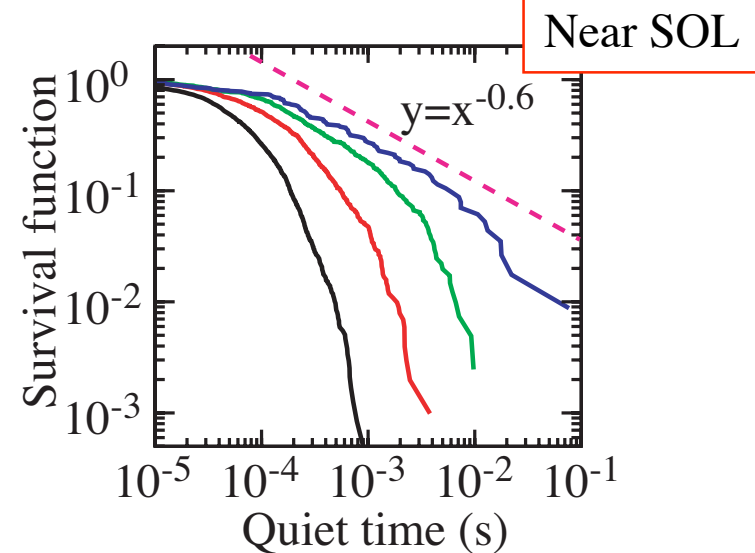 - ◆ obviate need for details of instability

Method (Carreras and Antar)

- Long-time series samples of I_{sat}, V_f in SOL from stationary scanning probe
- correlations, intermittency, self-organization

Results

- *Isat* data: Near SOL shows power-law tail on 'quiet time' between bursts
  - ◆ robust indication of SOC dynamics
- Far SOL - no SOC behavior

Plans (continued collaboration)

- dependence on plasma parameters, spatial locations

Near SOL

$y=x^{-0.6}$

Survival function vs Quiet time (s)

Far SOL

$y=e^{-155x}$

Increasing Event duration

Survival function vs Quiet time (s)

Edge transport- numerical simulation

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<u>Collaborative Program</u> provides close coupling to turbulence simulations/theory

- BOUT simulations (Umansky, Xu, Nevins, LLNL)

<u>Results</u>

- ◆ Experimental tests of BOUT predictions - "Quasi-coherent" mode properties, X-pt effects, compare w/UEDGE
- ◆ Indicates resistive X-point turbulence drive

<u>Plans</u>

- ◆ Allow "virtual" diagnostics in simulation output (core & SOL)
- ◆ Make simulation output available to C-Mod staff
- ◆ Predict effects on impurities (are there impurity 'blobs' and 'holes'?)

- Stotler (PPPL)
  - ◆ continued modelling of atomic physics of gas-puff imaging diagnostic (3D)

Neutral Dynamics

- Determines fueling
- Determines capability to pump the divertor (specifically He)
- Can affect core performance (edge cooling)
- May play a role in edge plasma transport

Status	Goals/Program

• Inherently 3D neutral distribution modeled - making progress
 • Wall pumping/inventory being measured - complex situation
     ◆ D retention,
     ◆ time scales,
     ◆ 3D nature of neutral pressures and flows
	• 1st principle models reproduce observations
	 • Optimize C-Mod cryopump
	 • Understand the role of wall & geometry
	 • Predict level of wall pumping
	 • Understand differences between high-Z & low-Z wall

Plasma-plugging demonstrated for ITER-like divertor

Background:

- C-Mod divertor closest to ITER in $q_{\parallel}$, plasma & neutral pressures, opacity to Lyα
- Neutral modelling of C-Mod divertor low by a factor of ~10 [Stotler (2002), Lisgo (2002)]
  - Neutral-neutral collisions?
  - neutral-plasma collisions?
  - plasma 'background' incorrect?
  - plasma plugging?
- *Need C-Mod to modeled properly for ITER*

New Results

- Gas conductances measured with and without plasma present using special capillaries/gauges
- Upper open divertor conductance
  - Reduced x2 by LSN plasma
  - Reduced x5 by USN, almost like closed divertor
- Lower diagnostic openings conductance
  - Reduced x4 by LSN plasma
- Data will serve to benchmark new 3D simulations
  - Lisgo (OSM-EIRENE), Stotler (DEGAS2)

Computation of Vacuum Conductance at Location "B-Bottom"
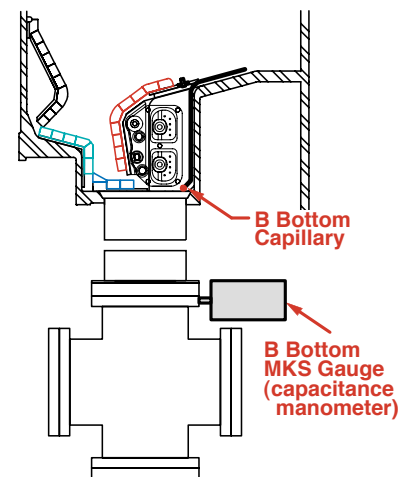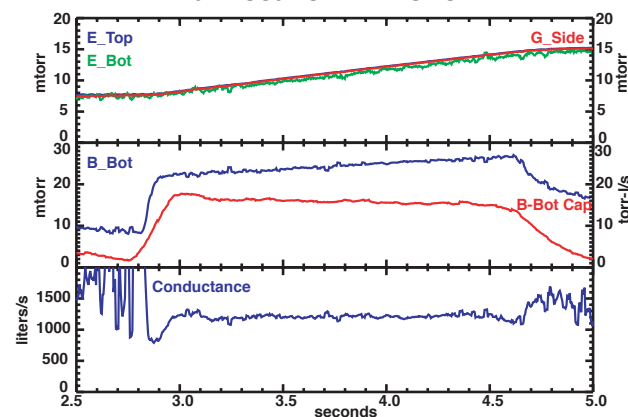
In-situ gas conductance and plasma flow experiments [PSFC/RR-03-6]

# Crucial benchmark against C-Mod divertor forces advance in divertor modelling

New Results

- OSM-Eirene (S. Lisgo) able to match C-Mod pressures within factor of 2
  - Plasma forced to match expt.
  - D_2->D_2 and D_2->D^+ critical*
  - recombination important*
  - 3-D geometry important
  - ExB flow circulation implied
  - *only ITER test of these effects

Plans

- S. Lisgo invited talk (PSI2004)
- D. Stotler to model 3-D neutral conductances in C-Mod divertor
- D. Reiter benchmark Eirenne radiation transport on C-Mod*
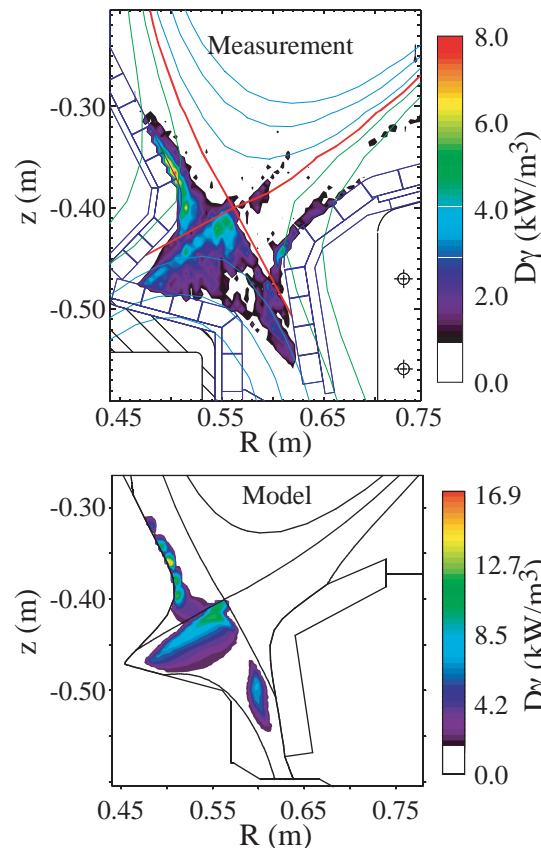
Plasma 'Background' Dγ light from OSM-Eirene Modeling [Lisgo (2003)]
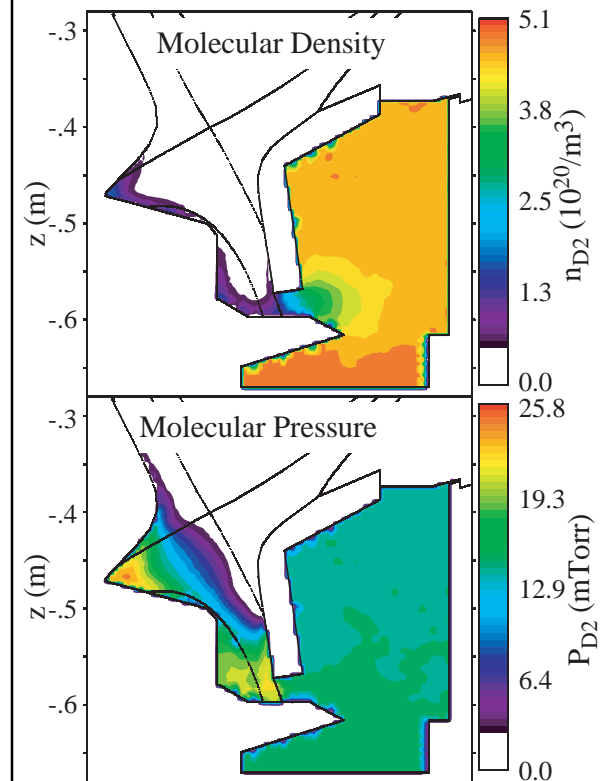
Neutral Density and Pressure Distributions [Lisgo (2003)]

Investigation of D/T retention in a high-Z tokamak is being pursued at MIT

Background

- More data is needed to predict level of T stored in ITER
- C-Mod provides part of high-Z experience

Old results (Wampler[1] tile analysis)

- D/B levels ~ 10 x lower than C tokamak
- D/Mo levels even lower.
- D retention NOT largest at inner divertor
- Fraction of fusion T retained < 0.2% without any specialized removal applied

Plans

- Exploring experiments/techniques to
  - Determine shot to shot wall-pumping,
  - Measure D deposition on tile sides (ITPA)
  - Measure in-situ D retention (w/Whyte/UW)
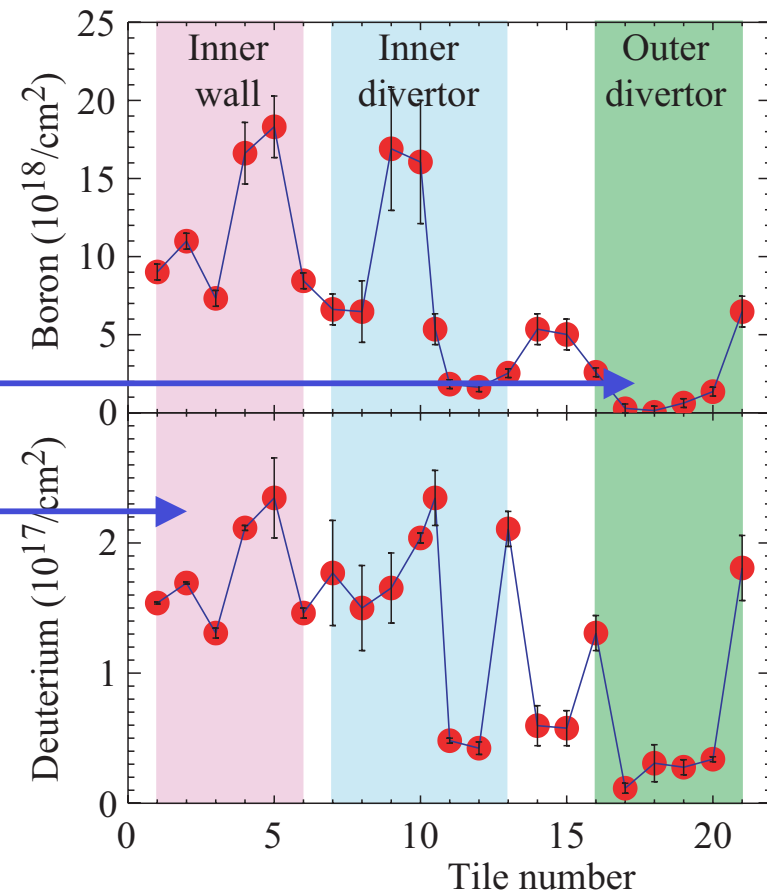
[1]JNM 266-269 (1999) 217

Impurity transport

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- Determines the core dilution/radiation
- Determines divertor power dissipation
- Determines pumping of He
- Plays a role in tritium codeposition

| Status	Goals/Program
• Modelling predictions uncertain	• Improve characterization of underlying transport, ◆ radial, e.g. "holes" ◆ parallel
• Significant high-Z PFC experience	
• Wall sources are important because penetration to core is efficient	• Models reproduce experiment
	• Measure/characterize impurities at all points in their 'lifecycle'
• RF effects can be important	
	• Clarify important sources/sinks

Initial screening simulations reflect experiment

Goal

- Understand & control impurity
  - Sources
  - Erosion & depsoition
  - flows

Screening modelling (Chung, MIT)

- Penetration factor
  - (# reaching core)/(# launched)
  - Dependent on launch location
  - Dependent on density
  - Characteristics similar to experiments
    - Divertor better screened than main chamber
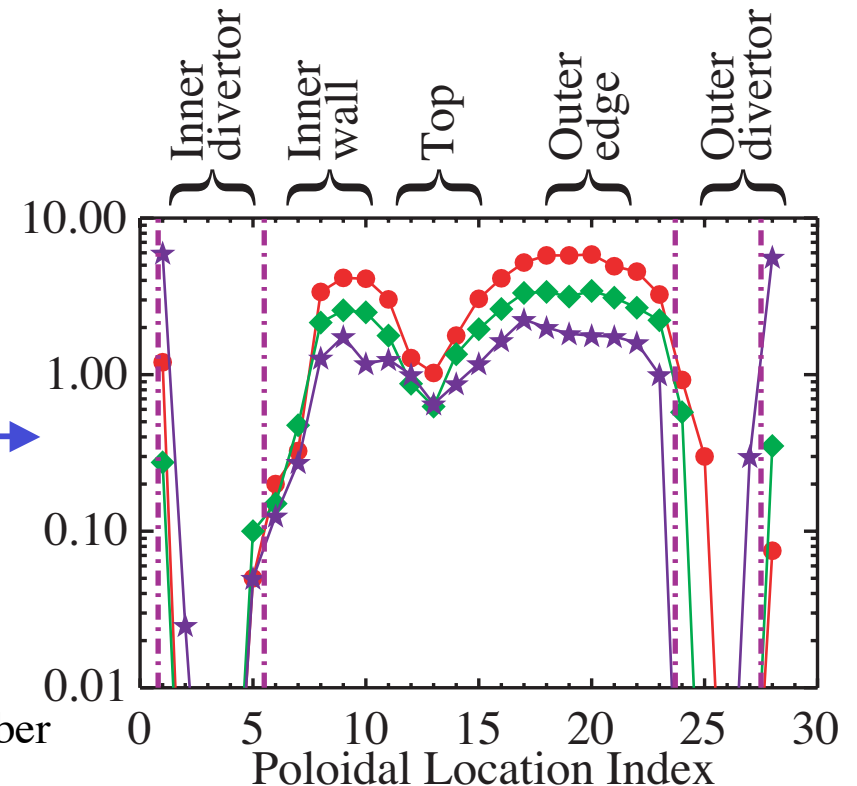
Plans

- Vary SOL characteristics to better match expt.
  - Flows
  - Strong radial transport

Penetration factor as a function of launch location

Erosion/redeposition studies from high-Z tokamak are important

Background

- C-Mod high-Z experience important for giving confidence in ITER W divertor.
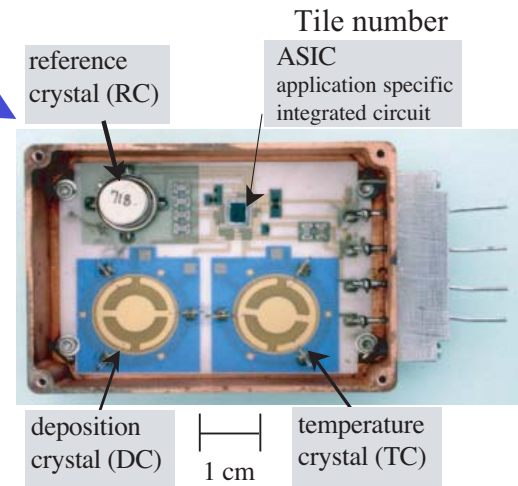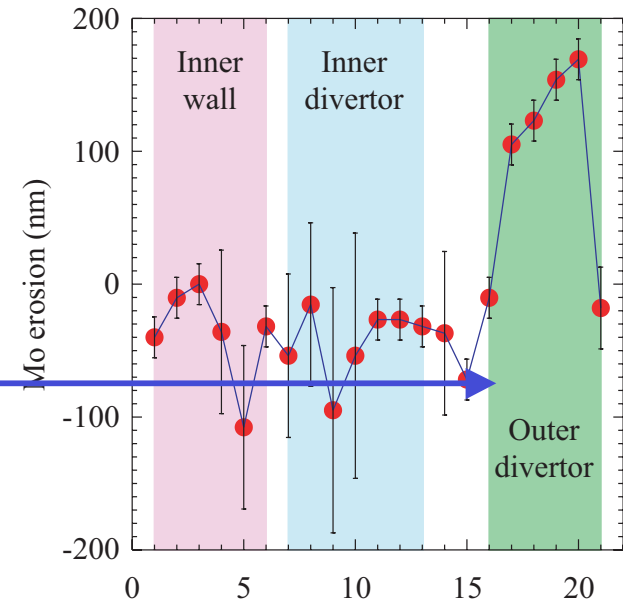
Results

- Wampler[1] used markers to determine erosion
  - ◆ Mo erosion only at outer divertor
  - ◆ Consistent with spectroscopic and probe measurements and physical sputtering[2]

Plans

- Addition of Quartz Crystal Microbalances
  - ◆ Buying JET-developed QCMs (w/DIII-D)
- Exploring development of in-situ diagnostic
  - ◆ Measures erosion and deposition
- Potential for new marker tile measurements

[1]JNM 266-269 (1999) 217
2Pappas et al, JNM 266-269 (1999)

reference crystal (RC)
ASIC application specific integrated circuit
deposition crystal (DC)
1 cm
temperature crystal (TC)

High heat flux handling & density control

- Important for the success of the C-Mod program
- Supports ITER for high-Z experience

Status	Goals/Program
- Presently 0.5 - 1.0 s pulse, 6 MW RF - melting at some divertor leading edges (shielded from the core) - Energy deposited will increase - Power increase by ~ x2, 5 seconds $\Delta T^o = q_\perp$ (W/m^2) x γ_{Mo} x (t(sec))$^{0.5}$ ΔT increases by ~ x4 - extrapolation => melting at strike points if nothing is done - No pumping, but H-mode densities might be too high for AT	- Develop improved surface temperature monitoring - Extend divertor heat-handling capability (~x2) - Test Tungsten-brush tiles - Extend power dissipation techniques (efficacy, low-n$_e$) - Cryopump operation

C-Mod continues to explore new concepts in particle and power control


cryopump

New optimized outer divertor
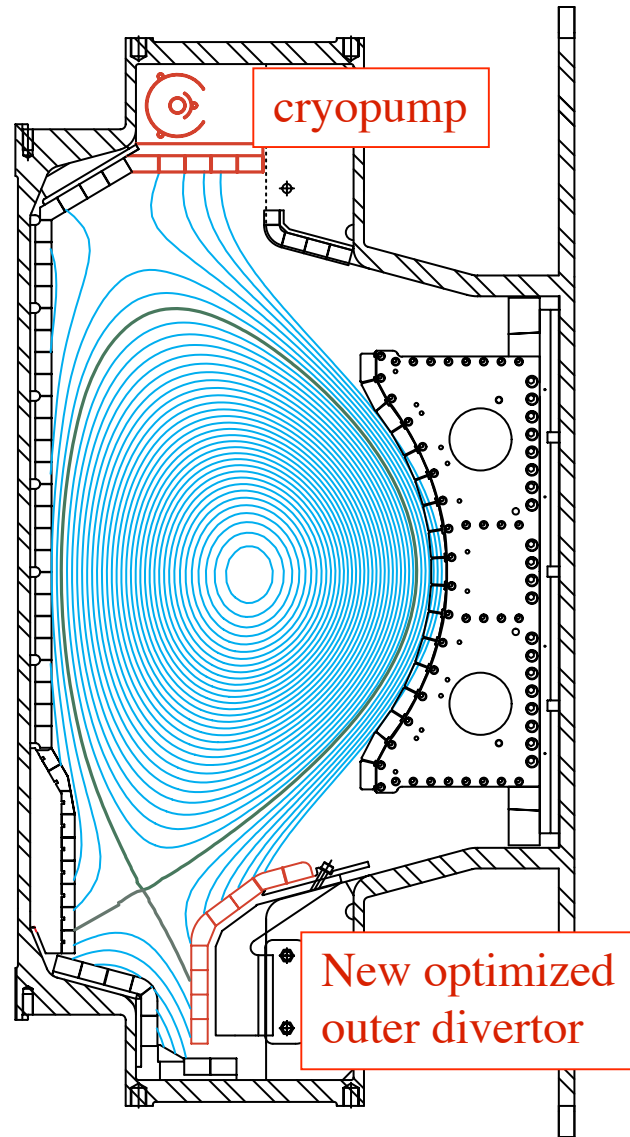
- Based on our experience with SOL transport and neutral dynamics, we will investigate a new combined particle and power control operation…
  - Near double-null operation
  - Heat load to primary divertor
  - Particle pumping to secondary divertor
  - Cryopump on secondary divertor, outer leg
- Why? And what for?
  - Open divertor still 'plugged' by plasma
  - Radial fluxes are high, feeding 2nd divertor
  - Separates power and particle control functions
    - Simplifies each divertor design

- We also plan to use advanced divertor target materials (high Z)
  - Prototype tungsten brush modules (near term)

Tungsten brush tile development and testing part of the C-Mod program

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Sample C-Mod W-brush tile

2.5 cm
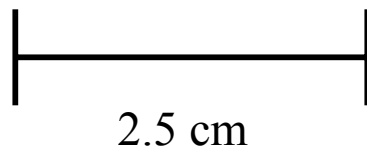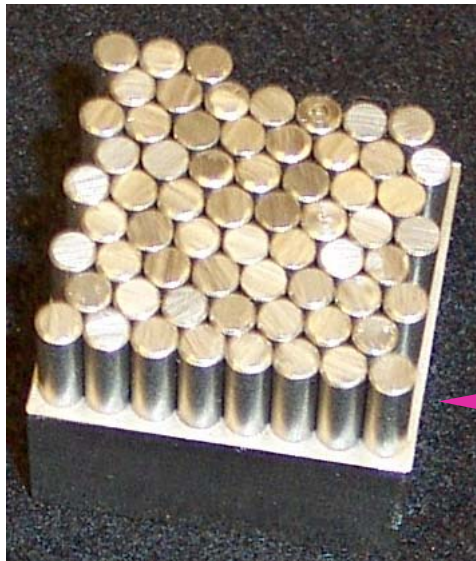
- Tungsten brush tiles have been proposed for BPXs
  - shown to handle up to 20 MW/m^2 steady state
  - resists melt layer formation
  - no tokamak experience

- C-Mod is working towards W-brush tile installation and testing
  - based on original Sandia design
  - collaboration with Sandia

- C-Mod design aimed at
  - simplified construction and manufacture
  - maximization of W/support interface

- Plans
  - 2 different tile designs being manufactured & tested
  - plan for installation of ~ 5-10 tiles next vacuum break

Divertor and Edge Physics: Summary

- Our intent is to continue to make fundamental contributions with emphasis on the following :
  - Steady state profile transport analysis to understand
    - Poloidal variations, machine scalings (ITER) -> uncover underlying physics
  - Edge flows importance in core confinement and possibly L/H thresholds
  - Turbulence studies
    - Turbulence relationship to large convective transport
    - Improved images/analyses/scalings/simulations & predictive capability,
    - Control if possible
  - Develop predictive capability for ITER SOL and thus power flows to PFC surfaces
  - Measure and model the 3D aspects of neutral dynamics
  - Characterize impurities at every step in 'lifecycle' - develop 'predictive codes'.
  - Develop separable divertor particle and heat control functions
  - Optimize high-Z first-wall and divertor for long-pulse & heat flux operation

- Providing vital support for overall physics program
  - Advanced Tokamak
  - Burning Plasma